Radiation Hardness and Linearity Studies of CVD Diamonds

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We report on the behavior of CVD diamonds under intense electromagnetic radiation and on the response of the detector to high density of deposited energy. Diamonds have been found to remain unaffected after doses of 10 MGy of MeV-range photons and the diamond response to energy depositions of up to 250 GeV / cm^3 has been found to be linear to better than 2 %. These observations make diamond an attractive detector material for a calorimeter in the very forward region of the detector proposed for TESLA.

1. Introduction

With the establishment of the Chemical Vapor Deposition (CVD) growth processes, diamond detectors started to be extensively investigated for their use for particle detection at future high energy and nuclear physics experiments. The developments were driven by the need for a radiation detector, particularly at the upcoming generation of experiments at hadron colliders like the Large Hadron Collider (LHC). The main problem diamond is faced with is its small charge collection efficiency, resulting in bad signal to noise ratios. Most of the studies, focused on the hadronic radiation hardness properties, have shown that diamond detectors suffer some radiation damage for fluences of neutrons, protons or pions above approximately $10^{15}/\mathrm{cm}^2$ [1].

At a possible future high energy electron positron collider like TESLA [2], the detectors in the very forward region are subjected to very high radiation doses, mostly electromagnetic radiation produced as beamstrahlung. Doses as high as several MGy per year are expected. Recently a number of studies have been published on the use of diamond in these regions as a possible detector material [3].

In this paper, after a description of the principle of operation of diamonds and the definition of some important parameters, we summarize the results concerning the radiation hardness, the Thermally Stimulated Current measurements (TSC) and the linearity tests.

2. Principle of Operation

Diamond has a number of properties which make it an attractive material for use in particle detection applications. The ionization produced by energetic charged particles passing through a thin diamond film, typically of the order of 300-500 μm thick, creates about 36 electron-hole pairs per μm of diamond. By applying a potential difference (typically 1V/μm) between the two electric contacts the charges start to migrate toward them. Due to impurities and dislocations in the diamond, some of the migrating charges are trapped and may contribute to space charge, which builds up and polarizes the diamond crystal. The charge induced on the contacts Q_{induced} is then smaller than the total charge created in the diamond Q_{deposit}.

A widely used figure of merit of the diamond material is its charge collection efficiency defined as $\epsilon = Q_{\mathrm{induced}}/Q_{\mathrm{deposit}}$. For current diamond material the charge collection efficiency is typically below 50%.

If the diamond is exposed to high levels of ionizing radiation, additional defect may be created

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in the diamond lattice, which may trap charge. These defects may be caused by impurities in the material (e.g. Nitrogen) or by structural damage to the lattice (e.g. dislocations, etc.). Several methods exist to study the defects and to better understand the mechanism of charge trapping in diamond. A particular powerful method one is the method of Thermally Stimulated Current (TSC). In this method, after having filled the traps at room temperature, the diamond is heated up. The rise of the sample temperature induces thermal detraping at a rate depending on the temperature and on the energy levels of the traps. A current proportional to the trap density and to the release rate is then observed between the contacts of the diamond sample. The TSC dependence on the temperature gives information about the energy levels and the density of the impurities in the diamond.
In addition to maintaining a good charge collection efficiency, a detector to be used in a high radiation rate environment also has to show a linear response to large energy deposition. This is particularly important for the application of this material in a possible forward detector at a linear collider, where energy deposits over many orders of magnitude are to be expected.
In the following sections, we summarize studies and present results for both radiation and linearity issues for diamond detectors. For a more detailed description of the analysis see reference [3].

3. Radiation Hardness

The response of CVD diamonds to uniform ionization densities has been measured using the setup shown in figure 1. The diamond samples were metalized with Ti/Pt/Au electrodes on both sides and placed in front of a collimated ^{90}Sr source which delivers electrons up to a maximum energy of 2.28 MeV. In order to guarantee that only signals from ^{90}Sr decay electrons which penetrate the diamond are recorded, a silicon trigger counter is placed behind the diamond sensor. The diamond signal is amplified using a charge integration amplifier circuit and can be viewed on a digital scope or recorded on a computer for future analysis. From the measured charge, one can estimate the charge collection efficiency.

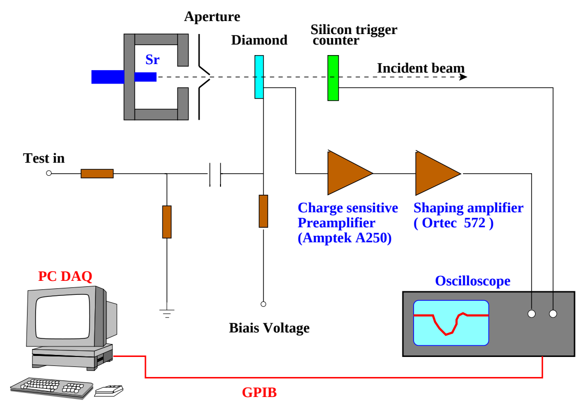

Figure 1. Charge Collection Efficiency Measurement Setup.

Three Diamond samples were exposed to electromagnetic radiation with two different ranges: below and above the threshold for non ionizing damages. A 10 KeV photon beam provided by the Hasylab facility at DESY with an average dose rate of 14 Gy/s was used to irradiate two diamond samples for doses up to 1.6 and 6.8 MGy. A third diamond sample was sent to a ^{60}Co irradiation facility which provides photons with energies of 1.17 and 1.33 MeV. The diamond sample was irradiated with a dose of 10 MGy.
Figure 2 show the total relative charge collection efficiency for the three diamond samples for different irradiation doses. No indication of degradation of the diamond quality as a function of the radiation dose has been observed.

4. Thermally Stimulated Current

Using the TSC method several diamond samples have been studied for their defect structure. After irradiation the samples were exposed to photons from a weak 10 KeV source to create electron-hole pairs in the sample.
To measure the TSC, a nominal voltage of 50 V was applied on one contact of the diamond dur-

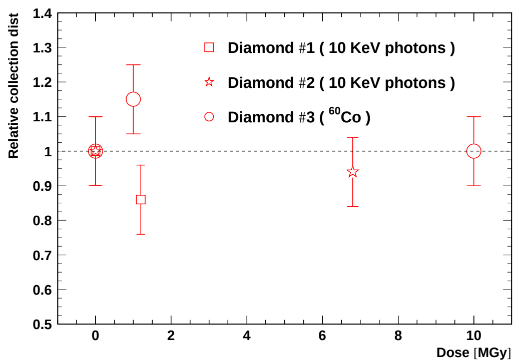

Figure 2. Ratio of the collection efficiencies measured after irradiation to the collection distance measured before irradiation for several diamonds and irradiation periods.

ing measurement and irradiation periods. The other contact was connected to a Keithley 6514 nano-A meter to measure the current. To generate the TSC, a remote-controlled heating element was used. The temperature was monitored using a thermocouple element read by a voltmeter.
Before heating the diamond, a fixed period of irradiation was used to create electron-hole pairs in the diamond and fill traps. For this purpose, the 10 KeV photon beam was directed on a 100 $\times$ 100 μm^2 slit. A remote-controlled shutter was placed between the detector and the slit to switch the beam on and off between data taking periods. For each acquisition sequence, an irradiation period of 60 s, well below the time period over which saturation effects become important, was done before the TSC curve was recorded. To study the influence of different areas on the diamond on the measurement an area of 1 mm^2 was scanned in steps of 100 $\times$ 100 μm^2.
Figure 3 shows a sample TSC curve of the evolution of the measured current with temperature. A fit to the TSC curves was performed to evaluate the energy levels, the frequency factors and the total density of traps. The deconvolution analysis yields to two energy levels equal to 0.35 and 1.19 eV.

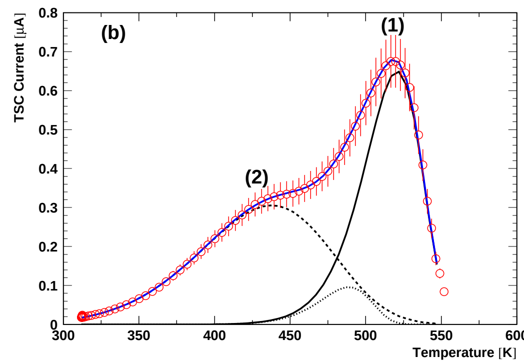

Figure 3. TSC spectra and associated deconvolution analysis. The deconvolution yields two energy levels at 1.19 eV (peak 1) and 0.35 eV (peak 2).

5. Response Linearity

The linearity of the response of the diamond detector was tested using the Hasylab synchrotron radiation facility at DESY. A diamond detector was placed in a 10 KeV photon beam which was intense enough to provide a high energy density two orders of magnitude larger than what is expected at the TESLA Luminometer. The beam intensity was about 2000 photons per bunch on a 300 $\times$ 300 μm^2 area. The beam was shone on a diamond surface of about 1 mm^2, defined by a copper mask. The photon flux on the detector for the maximum beam current (about 80 mA) corresponds to a deposited energy density in the diamond of about 7.5 GeV/cm^2 for a 300 μm thick diamond.
Figure 4 shows a sketch of the experimental setup used for the linearity studies. The diamond detector was read out using an Amptek A250 preamplifier, that was followed by an Ortec ampli-

fier/shaper with a 50 ns shaping time. The output signal of the amplifier/shaper was sent to a Lecroy 1182 ADC.

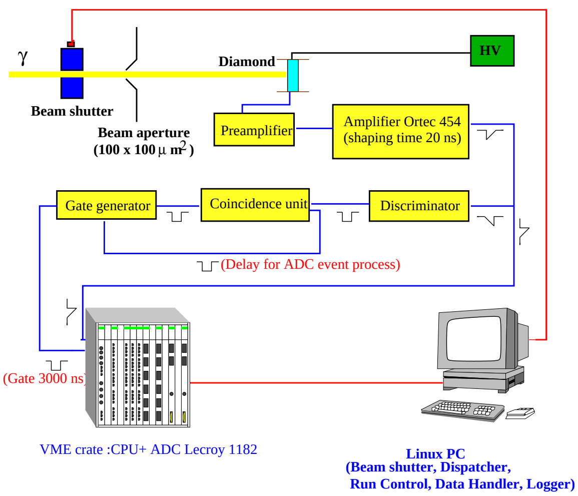

Figure 4. Linearity Setup

Figure 5 shows the variation of the measured signal as a function of the energy density in the diamond. One can clearly notice the linear relationship between the energy deposited in the diamond detector and the total collected charge. For low energy densities, one sees a non-linear behavior, ascribed to the pedestal. The bottom plot on figure 5 shows the relative difference Δ(ADC counts)/(ADC counts) between the data and the linear fit to these data.
These measurements show that the diamond detector is linear to better than 2% up to 7.5 GeV/cm^2 for a detector thickness of 300 μm.

6. Conclusions

Properties of CVD diamond detectors like their radiation hardness, their characterization using the TSC method and their linearity response to large amount of electromagnetic deposited energy, have been studied. Diamonds detectors have been found to exhibit a linear response to

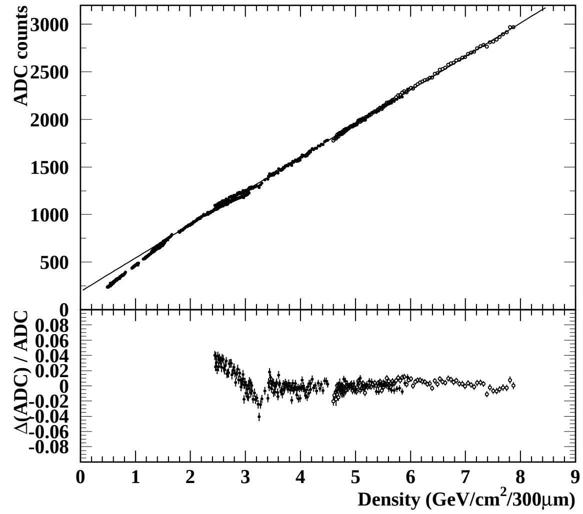

Figure 5. Diamond signal (ADC counts) as a function of the deposited energy density. The line shows the fit result. The bottom plot shows the relative difference Δ(ADC)/ADC between the measurement and the linear fit.

better than 2% for energy depositions of up to 250 GeV / cm^3.

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